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Night Wind Deliverable D.3.2 Main simulation report

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Night Wind - Deliverable D.3.2
Main Simulation Report

Tom Cronin, Henrik Bindner and Yi Zong

Risø-R-1661(EN)

Final

Risø National Laboratory for Sustainable Energy
Technical University of Denmark
Roskilde, Denmark
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"Grid Architecture for Wind Power Production with Energy Storage through load shifting in Refrigerated Warehouses"

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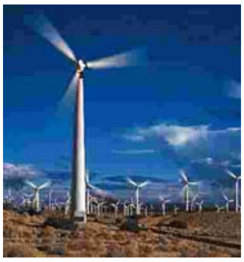

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PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Report number Risø-R-1661(EN) Final

Contents

Summary

This report represents Deliverable D.3.2 of Work Package 3 in the Night Wind project. The aim of this Work Package was to simulate a cold store (or number of cold stores) within a power system where there is a high degree of wind power penetration. The Night Wind Control System, developed as part of Work Package 5, was to be integrated into the simulations so that the wind power could be "stored" in the cold store with maximum benefit to the electrical network, utility or cold store owner.

To this end, the following have been accomplished:

- The Night Wind concept has been described in terms of demand side management.
- Input requirements and data have been specified and collected. Measured data from the existing cold store facility of Partner Logistics has been analysed.
- Component models for the simulations (including the cold store model itself) have been developed for the simulation platform, IPSYS.
- The Night Wind Control System (NWCS) from Work Package 5 has been developed so that it finishes computations within two minutes.
- Controllers (including the NWCS) have been operated with the cold store model within IPSYS.
- Simulations have been performed with the cold store model and an increasing penetration of wind power.

This report presents the results of the work undertaken in Work Package 3 which would have benefited from the additional time requested at the project meeting in March 2008, however, this extension of time was not granted. Nevertheless, the work that was possible is considered significantly complete, although it is acknowledged that there has been a delay in the presentation of this report. It should be noted that it was not possible to address the new aspects of Task 3.7 "Verification of simulation results" as there was no implementation of the night wind concept at the demonstration site (Task 7). Verification of the simulation of the present system has, naturally, been carried out and described in this report.

A summary of the work of WP3 is given below with relation to the contracted Tasks:

Task 3.1: Conceptual design & modelling:	**completed**
Task 3.2: Specification of input requirements & collection of input data:	**completed**
Deliverable D.3.1:	**delivered**
Task 3.3: Development and implementation of component models:	**completed**
Task 3.4 Implementation of controller models:	**completed**
Task 3.5 Simulation of the different designs in various scenarios:	**partially complete**
Task 3.6 Evaluation of benefits of each scenario:	**partially complete**
Deliverable D.3.2:	**delivered**
Task 3.7 Verification of simulation results:	**incomplete**

1 Introduction

By adjusting the control of cold store compressors so that, in times of high wind energy availability cold store temperatures are reduced, energy can be absorbed which otherwise would be considered excess and therefore lower the price of electricity. In turn, this energy “storage” increases the value of wind energy paving the way for market forces to drive a higher penetration. The proposal here is that the integration of renewable energy resources into the European electricity grid can be assisted by providing new facilities for energy storage, through the use of existing hardware and thus relatively little capital investment.

In Work Package 3 of this EU-funded project Risø DTU has been simulating electrical systems that enable the investigation of the interaction between cold stores and production from wind turbines. The simulation environment is Risø DTU’s in-house software package, IPSYS [1], which is designed for assessing networks with multiple sources of energy.

The Night Wind concept combines wind energy and refrigerated warehouses in an innovative way, in order to address some of the problems associated with high wind penetration. The warehouses are effectively used as energy storage devices by providing an additional means to help match demand and fluctuating supply. The Night Wind project aims to store wind power in the form of thermal energy by influencing the temperature control in refrigerated warehouses. In times of high wind supply the temperature can be lowered, using the “excess energy” and, additionally, decreasing future cooling demand. When wind power availability is low, the storage can be "discharged" by allowing the temperature to rise again. This has the effect of adding a "virtual battery" to the power system with relatively little investment in new hardware.

Cold stores currently schedule their ability to store thermal energy with the control signal being the electricity price but this is derived purely from the traditional demand-supply pattern which simply results in cold stores using most energy at night time. The challenges are, then, to:

- Simulate the co-ordination of cold store energy use with wind power generation to assess the impact on the amount of wind capacity in a system.
- Implement a controller that by some means of forecasting can decide when energy can be “stored” or when energy should be “released” because there is a higher value in having the ability to store energy at some future point in time. This is the Night Wind Control System (NWCS) which has been under development in Work Package 5. Fundamentally, the controller always has the food safety temperatures as overriding limits.
- Assess the means by which this co-ordination can be done, i.e. can a price signal be used which indicates the correlation of the amount of wind energy production with the electricity price, in a system with high wind penetration? This is part of the work being undertaken in Work Package 2.
- Consider how the enabling of cold stores to provide energy storage services to the grid can increase their competitiveness.

- Investigate the extent to which temperature ranges in cold stores can be extended so that their storage of thermal energy can be increased. Work Package 4 has been investigating the impact of temperature ranges on food quality.

There are three main parts to the work in Work Package 3:

1 Simulation of a single cold store, some local wind turbines and a grid connection – this enables the fundamentals of the control system to be worked out, together with some degree of verification using data from an actual cold store belonging to one of the project partners.

2 Implementation of a more advanced development of the control system (NWCS) to include the influence of wind power availability and the electricity price.

3 Representative simulation of a larger network to assess the impact of the Night Wind concept on a wider scale.

This report describes the concept, giving the background to the problems of increasing wind energy penetration in the European network. The simulation models together with the controllers being developed are explained and the results of the investigation to the extent it has been possible to carry it out will be presented. Conclusions are drawn that serve to guide any future work.

2 Cold stores and background to the simulations

Cold stores are major users of electrical energy. The cold store of Partner Logistics in Bergen-op-Zoom, which makes up the demonstration element in the Night Wind project, consumes around 12 million kWh per year. Whilst it is one of the largest in Europe, the fundamental principles of operation are common with other cold stores. (Note that the focus here is on cold stores with an upper temperature limit of -18°C and not chilled stores where goods are maintained above freezing.) The major power consumption comes from the compressors within the refrigeration units, whose main loads are the heat transfer from the external environment and from the goods coming into the store at around -7°C. The control system at present attempts to use cheaper night-time electricity, but invariably the compressors also need to run at times during the day to keep the temperature below the upper limit.

1.1 Benefits of a new control scheme

A new control scheme that takes account of the availability of wind power has potential attractions from a number of points of view:

The cold store owner may be able to:

- Receive an added return for his investment (i.e. owning a cold store) if he becomes a wind turbine operator as well :
    - when the price of wind power is low, use it for own consumption
    - when the price of wind power is high, sell it
- reduce operating costs by taking advantage of “excess” wind power.
- sell the ability to defer load as an ancillary service to the power system operator.

The power system operator may be able to:

- more easily absorb wind power into the system.
- achieve a increased ability to match actual and predicted generation.

The European network may be able to:

- increase the value of wind power.
- increase the penetration of wind power as a whole.

Above all, there is the potential to increase wind power integration at a low cost.

In order to make these models function as intended, the power price has to reflect the supply of wind power (which it does at a high enough penetration in a functioning market).

1.2 Requirements for a new controller

Traditional cold stores employ a simple thermostatic control with a certain hysteresis. The thermostat measures the temperature of the cold store air but the temperature of the product is not being taken into account. Since the air temperature is constant (within the hysteresis band of the thermostat), the product temperature will approach it asymptotically and stay almost constant as well.

This situation does not hold anymore if the goal of storage of energy is considered. The economical and technical value of any energy storage device depends on its storage capacity and power rating. The latter is linked to the speed of energy conversion, i.e. the speed at which the device can be charged and discharged.

The energy storage capacity of a cold store depends on the heat capacities of the stored products and the surrounding air. However, the volumetric heat capacity of products with a high water content – as most foods have – is more than 1000 times that of air. Even if a cold store is almost empty, almost all of the potential for energy storage lies in small variations of the product temperature. From this perspective, the cold store air is just a transmission medium and small interim buffer.

The charging and discharging rates are linked to the speed of heat transfer between the stored product and the air in the cold store. This speed is proportional to the temperature difference between the two. When the refrigeration machines (compressors) are operating, the air temperature quickly reaches a lower equilibrium T_{LE} some degrees below product temperature T_P, where the available cooling power equals the heat transfer from product to air plus the heat transferred from the outside. This equilibrium point will then slowly move towards lower temperatures as the product itself becomes colder. Once the refrigeration equipment is turned off, the air temperature quickly rises towards a second equilibrium T_{HE} – this time above product temperature - where the heat transfer into the product equals the heat transferred from outside the cold store. As the product temperature slowly rises, this equilibrium moves towards higher temperatures as well.

In order to achieve the highest possible charge rate, the lower setpoint of the thermostat must be set equal to, or below, the lower equilibrium point T_{LE}, in order for the compressor to continuously stay on (maximum charge, 100% duty cycle). Lower charge rates can be achieved using setpoints between T_{LE} and T_P. Similarly, for the highest possible discharge rate, the upper setpoint of the thermostat has to be equal to or above the upper equilibrium T_{HE} (maximum discharge, 0% duty cycle). Note that the location of the equilibria depends on product temperature, and that a duty cycle of 50% does not necessarily correspond to charge-neutral behaviour.

The use of food as a storage medium for thermal energy is quite demanding. Its temperature may vary only within well-defined limits; too low temperatures cause damage, while too high temperatures have a detrimental effect on food safety. To address these concerns, and to get an idea of the current state of charge, the absolute food temperature needs to be known. However, direct measurement of food temperature is not common practise as it may vary slightly within the product and is dependent on where the product is in the cold store. Contractually, cold stores are obliged only to measure the air temperature so the challenge will be to estimate the product temperature using product heat capacities, product throughput and historical air temperatures.

The goal of the new controller then, is to be able to use the high availability of wind power to lower the temperature of the product, whilst ensuring the food-safety limits of the food are not breached.

3 Cold store model and verification

3.1 The basic cold store model

The simulations have been implemented in IPSYS [1] a simulation engine developed by Risø DTU. IPSYS focuses on the discrete control of distributed energy systems (i.e. supervisory control) and the interaction between different system balances, such as electricity, heat, water etc. It is built in a modular way and consists of a core framework and a collection of system components, controllers and energy domains which can be plugged into the core. New types of components and controllers can be added to the simulation with relatively little effort.

The two main parts of the simulation built for the NightWind project are a representation of the grid connection and a cold store model. The grid representation (Figure 1) is modelled as a distribution feeder with connections to one or more wind turbines, the cold store and additional, lumped load. The focus of interest in the grid simulation lies with the interchange of power between the distribution feeder and upper voltage levels.

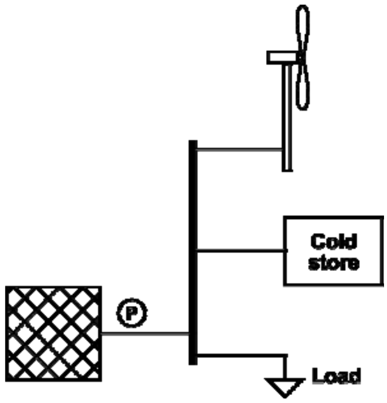

Figure 1. Simplified components of the simulation system.

The cold store model, shown in Figure 2, describes the heat exchange between three bodies – stored product, air inside the cold store and the environment. The refrigeration machinery consists of several identical units which can be switched on or off independent of each other. This enables operation under partial load. The product is represented not as a solid body, but as a loose stack of smaller bodies, yielding a relatively high ratio of surface to volume. The outside temperature is read from time series data.

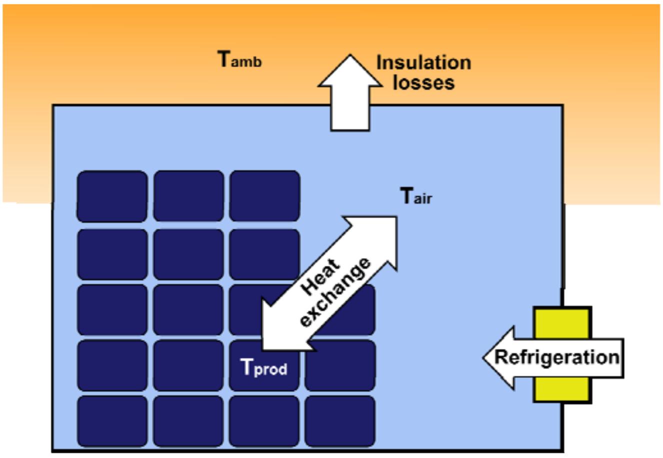

Figure 2. Heat transfer paths in the cold store model.

3.2 Model verification

As a means of partial verification, the results of a short and simple simulation of the cold store model in IPSYS were compared with the results of a similar simulation using the Coolpack/Dyncool software [2]. This was developed by the Department of Mechanical Engineering in the Technical University of Denmark and is a collection of simulation programs that can be used for designing, dimensioning, analyzing and optimizing refrigeration systems.

Comments on the simulations:

- Both simulations have a constant product temperature as this is the only way in which air and product temperatures can be modelled in Dyncool.
- There is a constant outside temperature of 20°C
- The cold store size represents the present size of the PAL facility, Bergen op Zoom
- Waste heat from the compressor motor is included in both simulations even though the motors in the PAL facility are outside the cold area.
- IPSYS does not, currently, support a varying COP.
- Single stage compressor (R404A refrigerant)
- No inward movement of product (i.e. no cooling load for reducing temperature of incoming goods).

The results are not for comparison with the PAL facility but only for comparison with each other.

The Dyncool simulation result is shown in Figure 3 and the IPSYS model result is shown for comparison in Figure 4 :

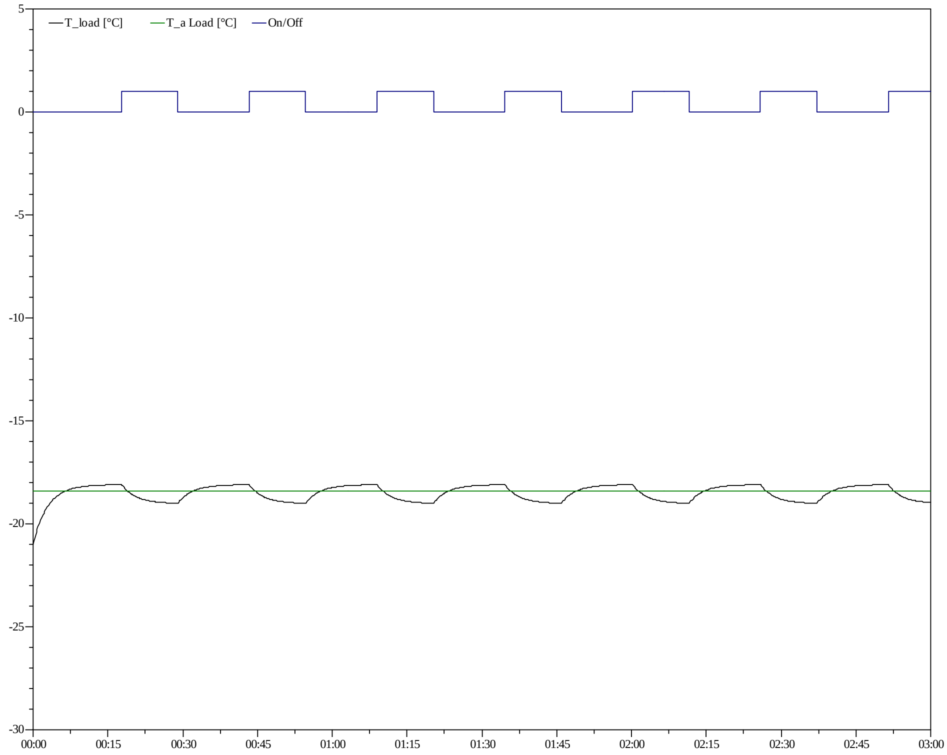

Figure 3 Coolpack/Dyncool simulation result - compressor activity, air and product temperature

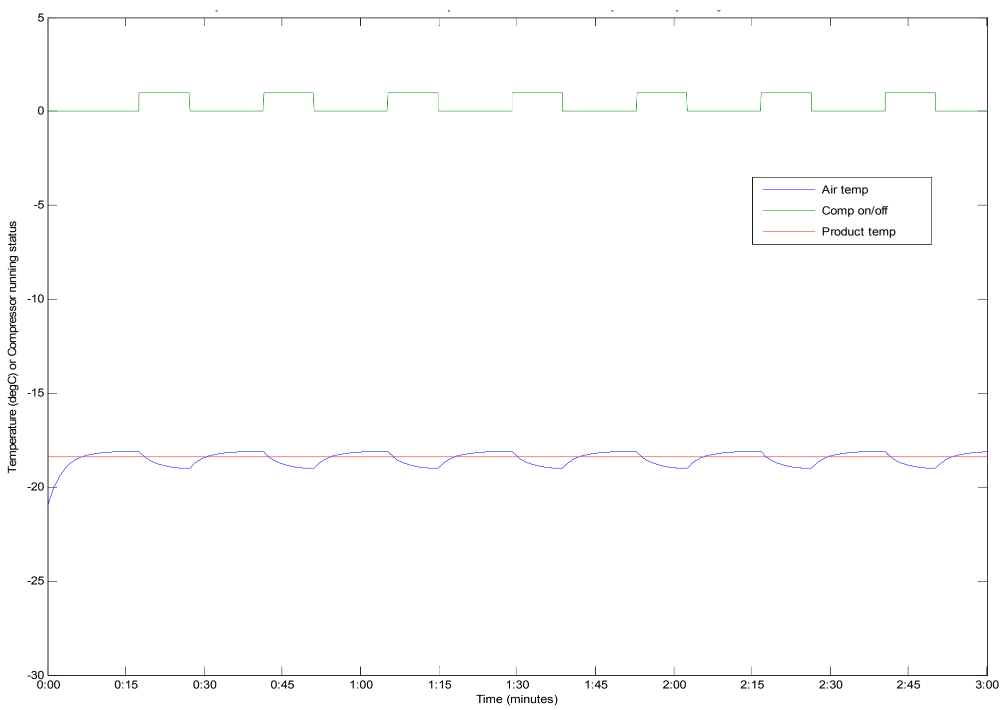

Figure 4 Output of IPSYS simulation of the same size of facility as with Dyncool/Coolpack

For the simulation of a three hour period of refrigeration, the energy use of the compressor for each platform is as follows:

Dyncool: 1140 kWh

IPSYS: 1157 kWh (+1.5%)

This gives a reasonable level of confidence that the IPSYS model provides a sufficiently accurate representation of a cold store's compressor energy consumption.

3.3 Assumptions

Even though it is believed this model is realistic enough to support the initial development of controllers, it is still incomplete and has a number of shortcomings. As the modelling work progressed, some of the following assumptions have been addressed.

- The model of the refrigeration unit is very simple. In a real-world refrigeration system, both the energetic efficiency (COP – coefficient of performance) and the cooling capacity depend on the temperature difference between evaporator and condenser. The present model assumes constant (fixed) COP and output, which is a reasonable first-order approximation if neither the outside temperature nor the store temperature are allowed to vary by more than a few degrees °C.
- At this stage in the development, the simulation did not yet include the product flow in and out of the store. As the heat capacity of food is much larger than that of the air in the cold store, almost the whole potential for energy storage is in changing the temperature of the product. "Leaks" in the storage system occur due to products being shipped off immediately after having been "charged", i.e. cooled below the required temperature. These are inevitable to some degree, but can possibly be reduced if the control strategy considers product flow.
- The heat flow model currently assumes perfect heat exchanges between product surface, cold store air and outer walls, as well as a homogenic air temperature throughout the whole volume. Because of forced convection present in the cold store, this is a reasonable first-order approximation, but the simulation can be expected to slightly exaggerate the amount of heat exchange between product and air.
- The cold store is modelled as a single contiguous volume, representing the main storage area. In practice, cold stores have separate sections for initial (fast) refrigeration, intermediate storage and loading/unloading. These other sections operate at different temperature levels, and may not be able to participate in any load-shifting control scheme applied to the main area: Fast refrigeration of incoming products, for example, cannot be deferred, even if the main area is "discharging", i.e. the temperature rises.

4 Cold store controllers and the NWCS

4.1 Introduction

A conventional cold store will have a thermostatic control, as has been described in the preceding sections. The idea behind the Night Wind Control System is not to replace this control but to generate set points for the existing controller so that wind energy is stored in the most appropriate manner.

Development of the NWCS has been done in Work Package 5, by CENER in Spain. This work has been in conjunction with Work Package 3 as the NWCS uses a basic version of the simulation model built developed in WP3.

During the collaboration it was realised that the lengthy processing times of the NWCS would be a challenge for carrying out timely simulations (it was not regarded as a problem for implementation as a real-time commercial product was outside the scope of this project). It was identified that the platform used, Matlab [3], was most likely the cause of the extended running times and it was therefore decided by Work Package 3 to translate the code into C++, which is also the language of the IPSYS simulation platform. By doing this, the running time was cut from two and a half hours down to around two minutes.

The work described here builds upon that carried out by CENER in Work Package 5.

The concept of the NWCS and simulation model interface is as shown below in Figure 5.

The NWCS operates on a "day-ahead" basis. That is, it uses forecast wind power, forecast ambient temperatures and electricity prices for the next 24 hours to compute the optimal operation of the cold store.

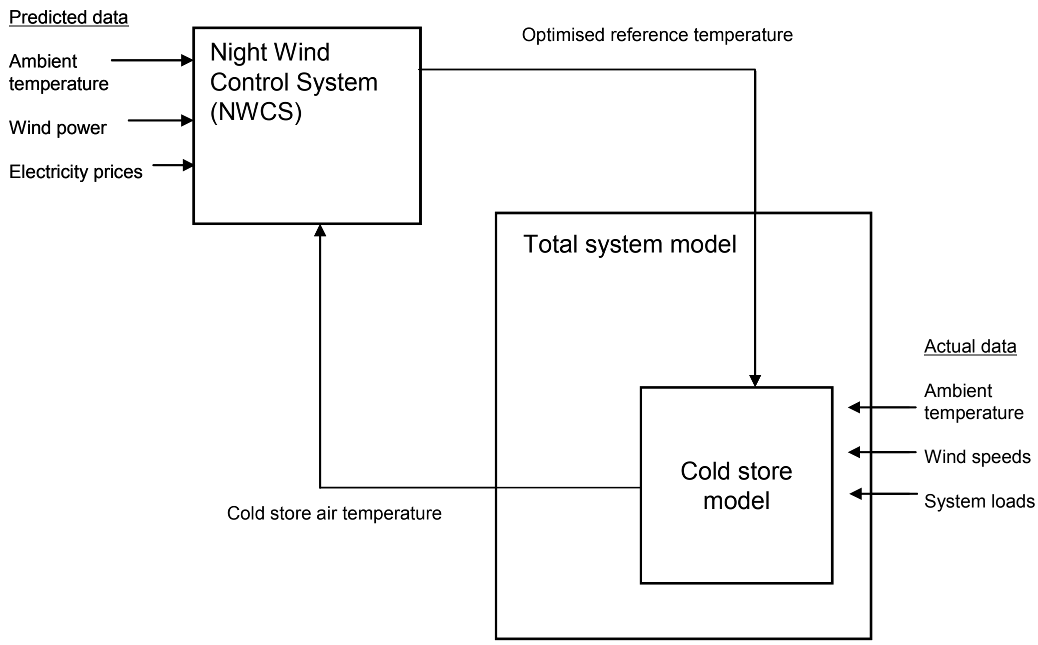

Figure 5 Interfacing of the NWCS with the system model

The electricity buy and sell prices are known at 12 o’clock each day for the following day in hourly intervals. Thus there is an actual horizon of 36 hours where all the information (forecast or agreed) is known. The NWCS thus optimises for the next 36 hours even though it is actually runs every 24 hours as shown in the timeline in Figure 6.

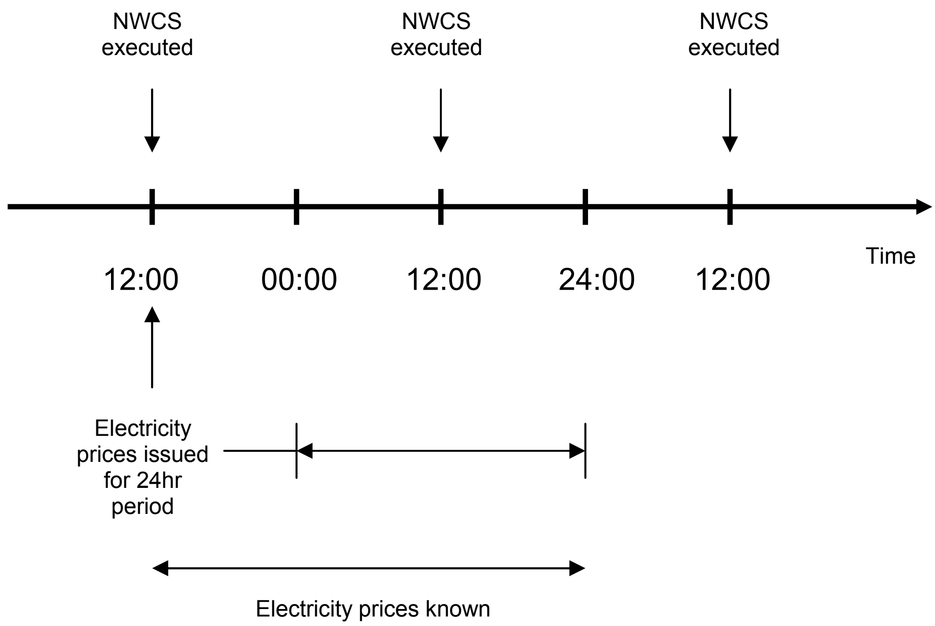

Figure 6 Timeline for execution of NWCS

The core routine in the NWCS is a Genetic Algorithm (GA) which uses the principles of genetics and survivability to optimise the reference temperature given the ambient temperature, wind power and electricity price forecasts. This use and implementation of Genetic Algorithms is described in the sections below.

4.2 Genetic algorithms and control

In this project, a new control strategy based on a Genetic Algorithm (GA) was used to set the temperature in refrigerated warehouses to a level that was derived from the actual balance between wind energy production and actual electricity demand.

The objective of the control aspect of this project is to minimize electricity consumption costs by optimizing the cooling strategy depending on predicted wind generation and grid electricity prices and continually adjusting the power taken from the grid/from the wind turbines. In some cases, it may actually be profitable to cool during the daytime; in other cases, it may be cheaper to export the electricity produced to the grid and then buy it back as needed. In order to safeguard the requirement to maintain the temperature of the frozen products, there are three compressor sets in the refrigerated warehouse. One compressor is always working and the second compressor is on for regulating the air temperature between -21 ºC and -18ºC. If the air temperature is higher than -18ºC, then the three compressors are working at the same time. Each compressor set consumes 375kW at maximum cooling capacity.

The genetic algorithm is a search algorithm based on the mechanics of natural selection and natural genetics. It is often applied to solve various optimization problems that are not well suited for standard optimization algorithms, including problems in which the objective function is discontinuous, non-differentiable, stochastic or highly nonlinear. It has been proved that the genetic algorithm can not only provide approximate global optimum solution, but also it does not require any training of data and will never have convergence problems [4]. The general concept of a genetic algorithm can be illustrated as in Figure 7 and the detailed algorithm for a GA based on minimum cost in the project is given below:

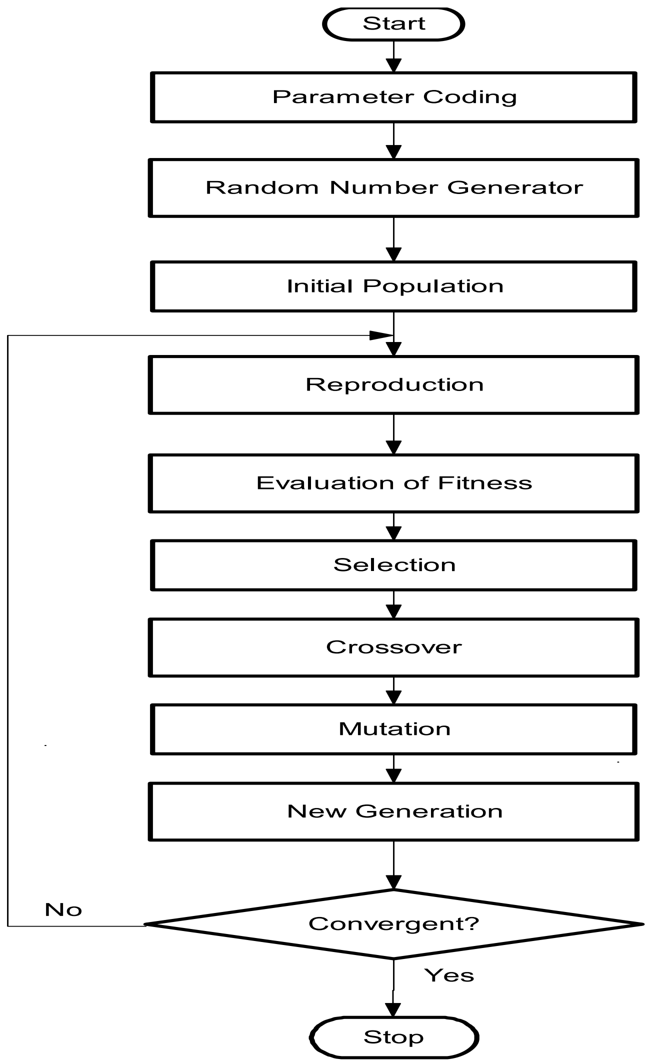

Figure 7 General principles of a genetic algorithm

The principal steps are:

1 Generation of the random population. This is the reference air temperature for the 1st generation and is a random number within the allowed interval of air temperatures (e.g. between -21 and -18 °C). This initial population is selected to ensure sufficient diversity to find the optimum solution efficiently. The population size also affects the performance and efficiency of the process. Too small and the result is poor due to insufficient sample size. Too large and the

rate of convergence may be too slow. In this case, the evolution was processed for 100 generations with a population size equal to 73 ($2n+1=2\times36+1$, where n is the number of design variables, i.e. the optimized reference air temperatures in the next 36 hours).

2 Reproduction. A representation of the cold store within the NWCS is then used to find the cold store “response” to the various reference air temperatures.

3 Evaluation of fitness. By calculating the cost, the fitness of each individual is assessed and the best one is then transferred to the next generation.

4 Selection. The roulette-wheel selection strategy is used as this preserves the diversity of the population and the best individuals survive to the next generation.

5 Crossover. This operator exchanges genetic information among the population. The higher the crossover rate the more quickly new structures are introduced into the population. There is, again, a balance between high and low crossover rates to achieve the best solution in an acceptable time. Here, a two-points crossover was used with a value of 0.6.

6 Mutation. The mutation operator replaces old individuals with new ones for the next generation which increases the variability of the population. Too much variability and the process to find the optimum solution will be lengthened. Too little and near-optimal points can be missed.

7 Convergence check. This is done by measuring the diversity of the population and comparing the difference between the best fitness and the average fitness to see if it is less than the specified error. If not, then steps 2 to 6 are repeated.

Many speed trials were performed to find compromise values for the various operators that gave an acceptable compromise between performance and accuracy.

4.3 Temperature control and genetic algorithms

The control of the compressors in a cold store is, at present, an ON/OFF decision. (Some manner of variable drive for one of the compressors at PAL’s installation in Bergen-op-Zoom was being considered at the time of this project but is has not been modelled.) The air temperature reference value has a tolerance band applied to it: if the air temperature goes above the upper tolerance then the compressors are switched on, if it goes below then the compressors are switched off. This tolerance band is plus/minus 0.1 °C.

The reference air temperature is optimised for hourly intervals for the following 36 hour period. All the information concerning electricity (buy and sell) prices, ambient temperature and wind power forecasts is contained in input files available to the NWCS. The cold store parameters (store volume, product volume, etc.) are contained as constants in the representation of the cold store within the C++ version of the NWCS. A library of genetic algorithm components was used to find the optimised reference temperature (“GAlib” [5] was used in the C++ version of the NWCS). Most of the work was with two classes: a genome and a genetic algorithm.

The flow chart of the GA-based control in the NWCS is shown in Figure 8.

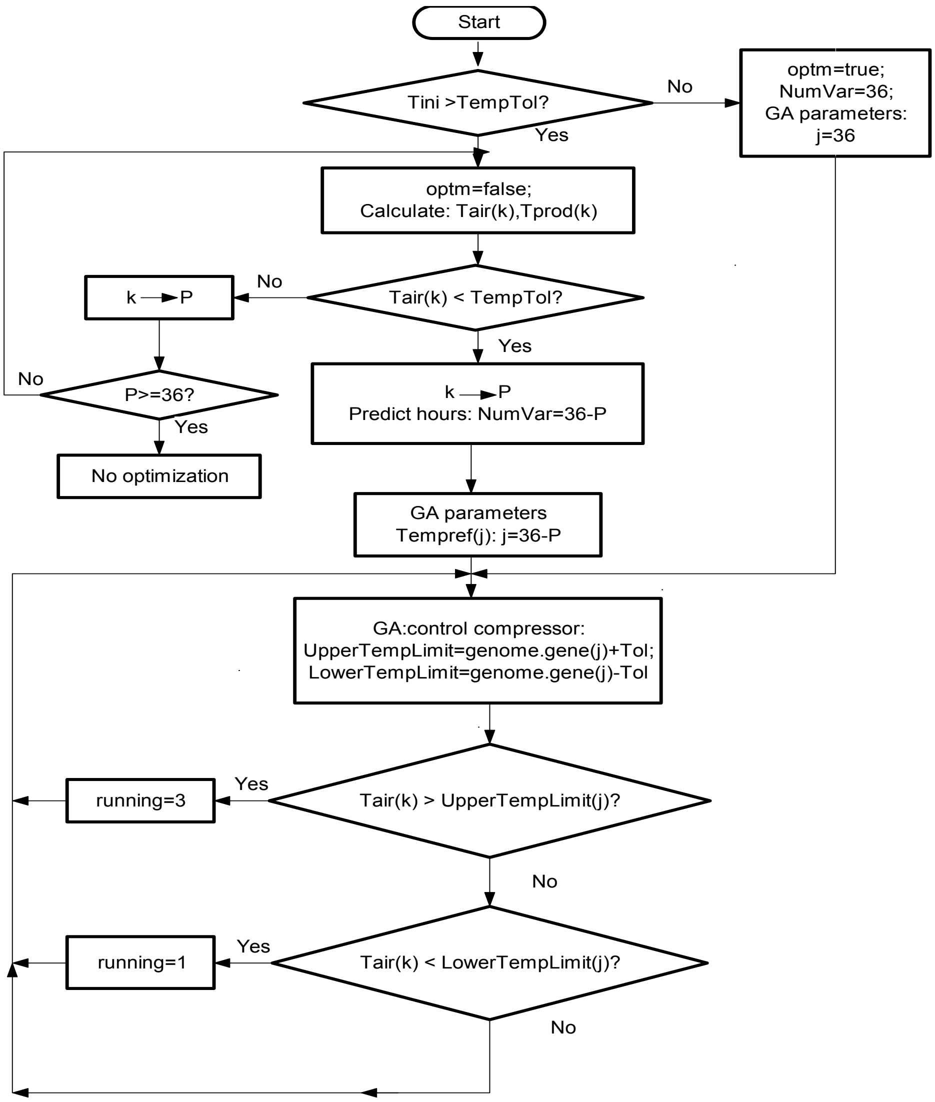

Figure 8 Flow chart of the GA-based control sequence in the NWCS

The initial population is the first reference temperature in the algorithm for the next 36 hours. This is compared to the tolerance temperature (*TempTol* in Figure 8) and when it is higher then the compressors are turned on and the Genetic Algorithm is bypassed (*optm = false* in Figure 8). Else the compressors' performance is optimised by the GA and the range for the air temperatures (e.g. -21 ºC and -18ºC) determines the limits for the reference temperatures (*UpperTempLimit = genome.gene(j) + Tol* and *LowerTempLimit = genome.gene(j) - Tol*).

4.4 Initial trials with the NWCS

Three scenarios have been trialled with the NWCS, each with different initial air temperatures. The control and Genetic Algorithm parameters are shown in Table 1.

No. of scenario	*Initial air temperature*	*Tolerant temperature*	*Population size*	*The best generation*
1	-19.1	-19	73	97
2	-18.4	-19	73	30
3	-18	-19	–	–

Table 1 Temperature control parameters and the best generation for the three scenarios

4.4.1 Scenario 1

The results of the NWCS optimisation are shown in Figure 9 and it shows the variation of reference temperature over the 36 hour period of optimisation.

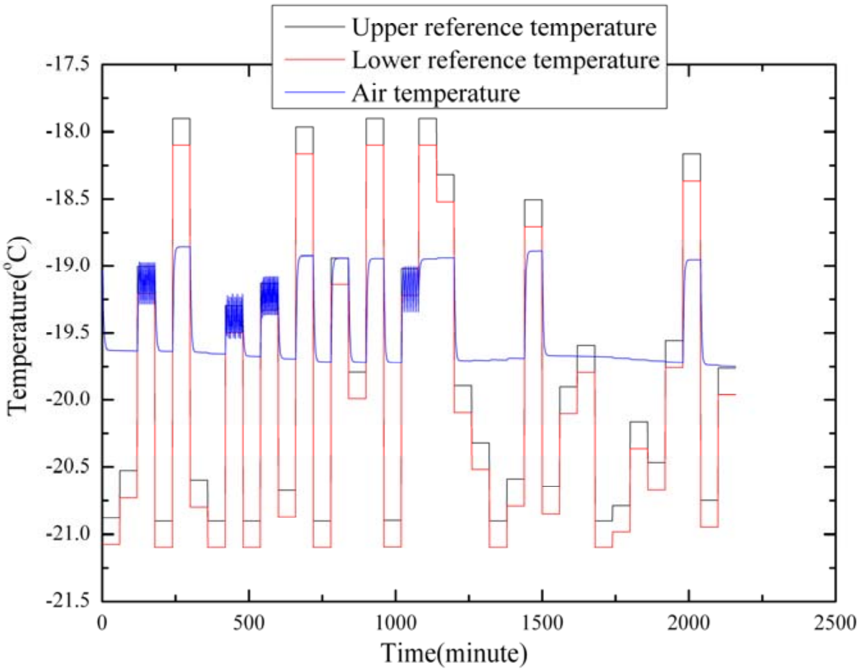

Figure 9 Scenario 1: Optimised upper and lower reference temperatures (36 hours)

As the initial temperature (-19.1°C) is lower than the tolerant temperature then the GA is implemented from the beginning and the pattern of compressor activity can be seen in Figure 10. The consumption of electricity by the compressor is in four distinct periods and, with reference to Figure 11, it can be seen that the wind power can be sold in the other periods of time. The result is that the best fitness function is negative (-1918.79€ as

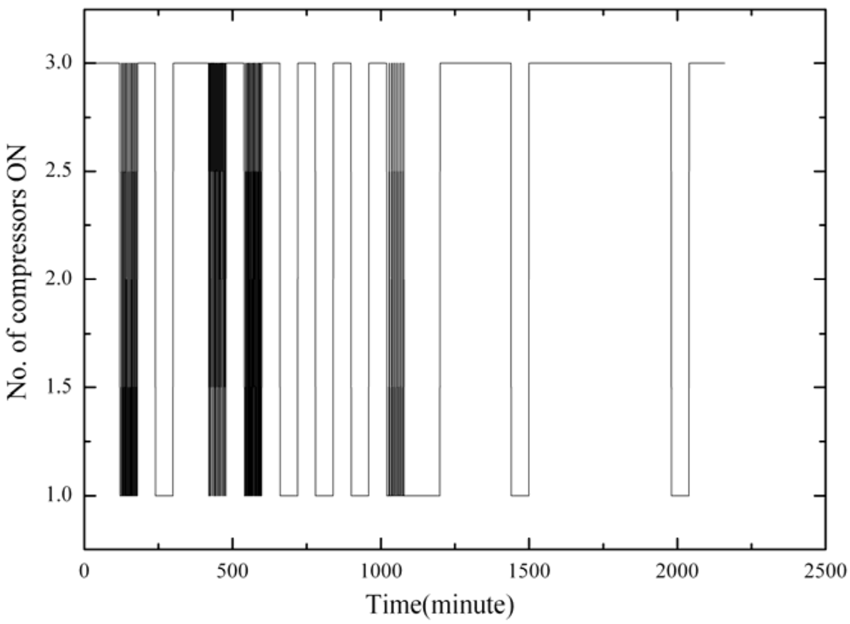

Figure 10 Scenario 1: Number of working compressors

obtained in the 97th generation). This means the owner can sell this energy and make a profit.

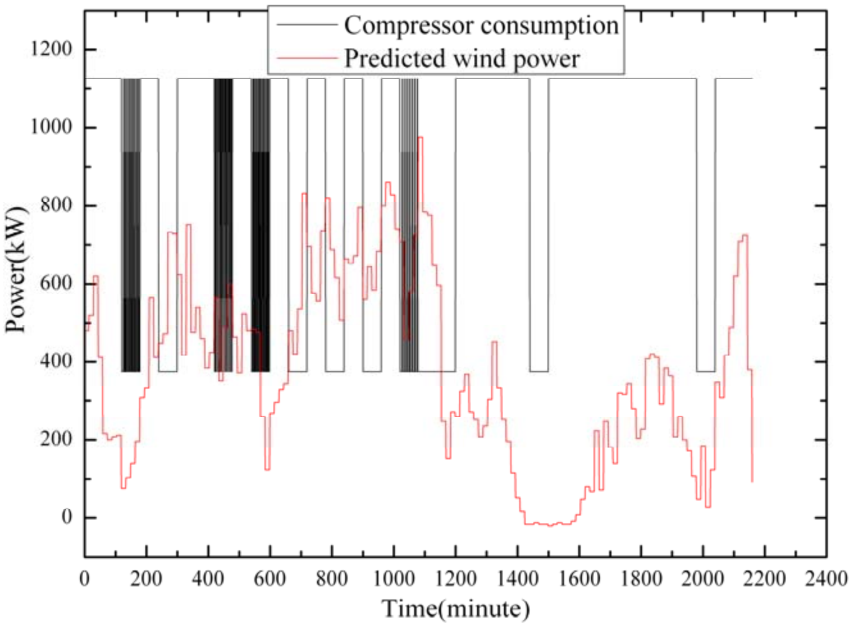

Figure 11 Scenario 1: compressor consumption and predicted wind power

4.4.2 Scenario 2

In the second scenario, the initial temperature is set to -18.4°C which is 0.6°C above the tolerant temperature and thus approximately 11 hours are needed during which the compressors are running continuously to lower the temperature, before the Genetic Algorithm is called upon and optimisation begins. So there are only 25 hours left for the optimisation process and the results are shown in Figure 12.

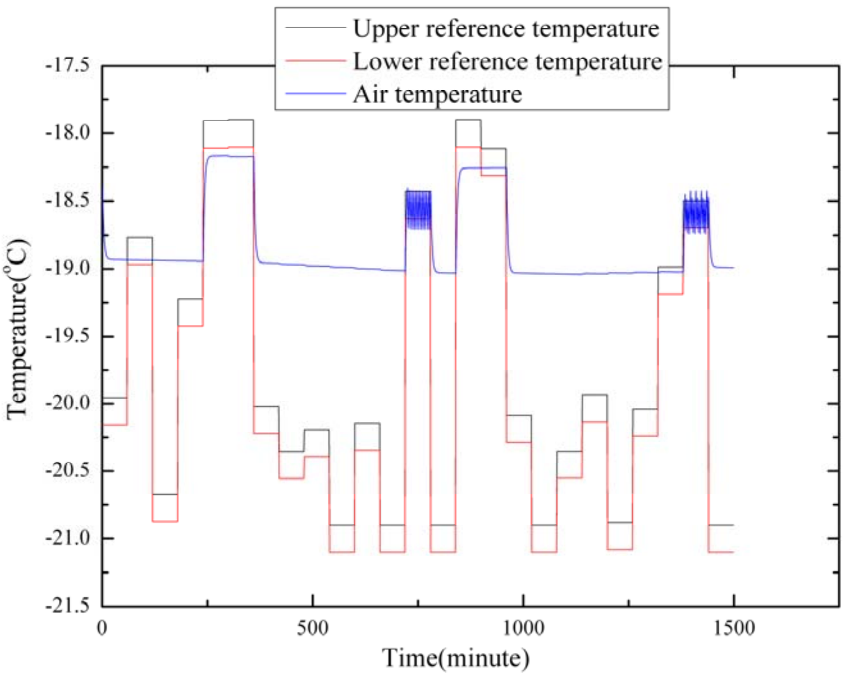

Figure 12 Scenario 2: Optimised upper and lower temperatures (25 hours)

The pattern of compressor use is shown in Figure 13 and when this is superimposed on the wind power generation it can be seen that there are two distinct periods where the compressors are needed and thus the wind power can be sold at other times (as shown in Figure 14.

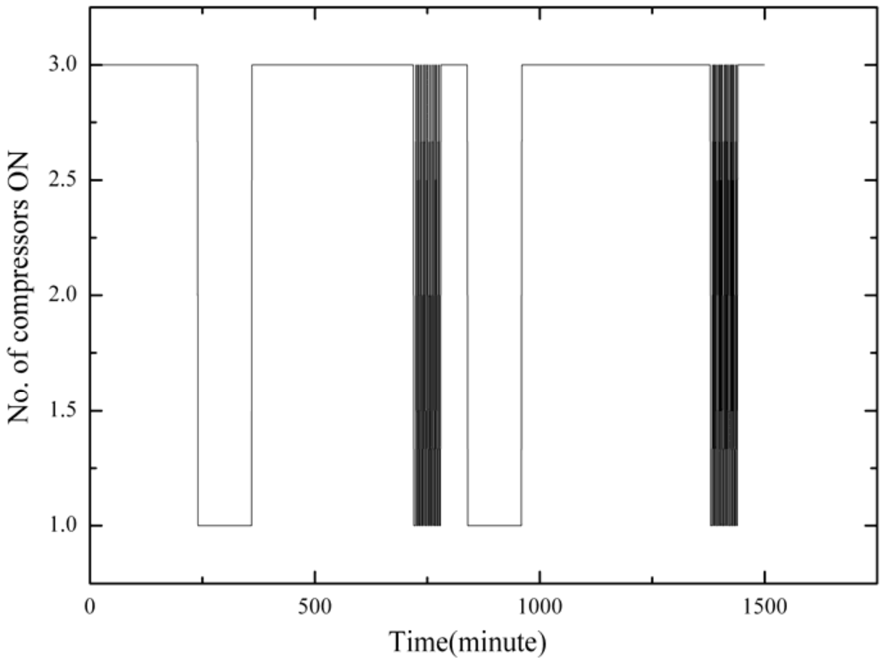

Figure 13 Scenario 2: Number of working compressors

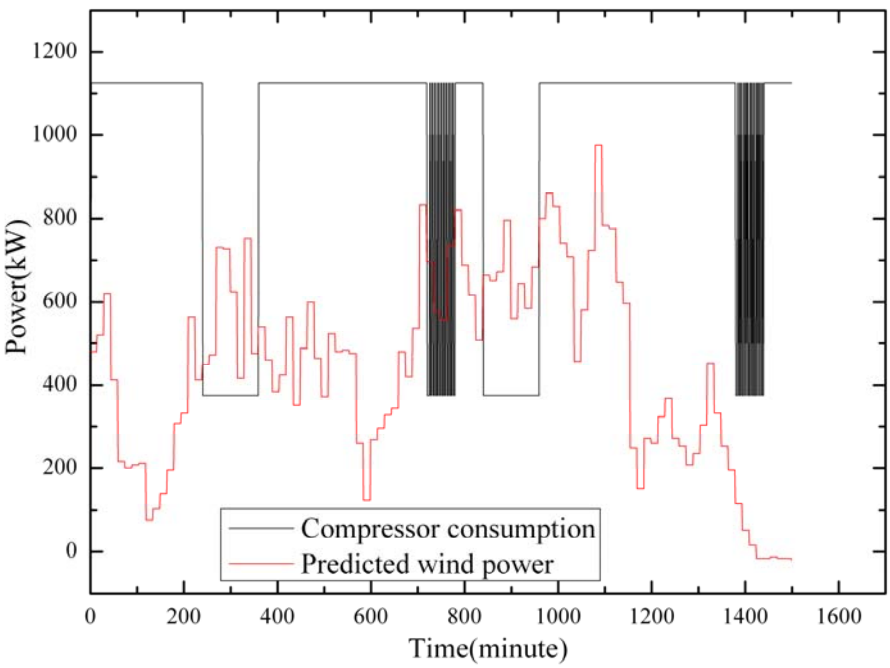

Figure 14 Scenario 2: Compressor consumption and predicted wind power.

The best fitness function is negative (-1209.71€, obtained in the 30th generation), which indicates the grid operator can also benefit but not as much as in Scenario 1.

4.4.3 Scenario 3

Here, the initial temperature is 1ºC higher than the tolerant temperature and, again, the compressors are required to be on to cool down the air temperature to within limits. However, in this case it takes longer than the 36 hour horizon to lower the air temperature to the tolerant temperature or less, and thus the optimising routine is never called upon.

4.5 Discussion, recommendations and conclusion

The NWCS has been translated into C++, developed further and brought to a stage where it is totally operational. Whilst not yet fully integrated with the IPSYS simulation platform, it has been shown that the NWCS in the C++ environment is capable of generating the required reference temperature data for input into the cold store model in a timely manner.

The primary runs of the NWCS have demonstrated that sensible patterns of compressor switchings are achieved and that the controller can make advantageous decisions for the use of wind power when it has access to the electricity market data.

The NWCS is very close to being realised within IPSYS, where its full potential can be fulfilled. In very little time, the systems will be working together and it is unfortunate that no additional time was forthcoming for this work, which otherwise promised to yield extensive results.

5 Simulation scenarios

There are four main categories of simulation that should be carried out:

- Initial simulations with the cold store model and a standard thermostatic controller in order to investigate the behaviour of the model and understand the fundamental heat flows involved.
- Simulations including the introduction of wind power and the “Wind noticing” controller, which demonstrate the integration of increasing wind turbine capacity in a system. This enables the power flows to and from the grid to be studied.
- Basic simulations with the model of the PAL facility in Bergen-op-Zoom. Again this uses a straightforward thermostatic controller to produce results that can be compared to data that has been measured at the actual cold store.
- Simulations with the Night Wind Control System at both a local and national/European level.

6 Simulation results

6.1 Initial simulations with cold store model

The first simulations were done using purely thermostatic control, i.e. it was only the temperature of the air that switched the compressors on or off.

6.1.1 Cold store performance and response in the simulation

The first very noticeable result in cold store performance from the simulations was the sensitivity of compressor cycling times to the temperature limits that were set for the air temperature. The cycling of the compressors predicted in the simulations is shown in Figure 15. Clearly, the tighter the required temperature band, the more frequently the compressors have to switch on and off.

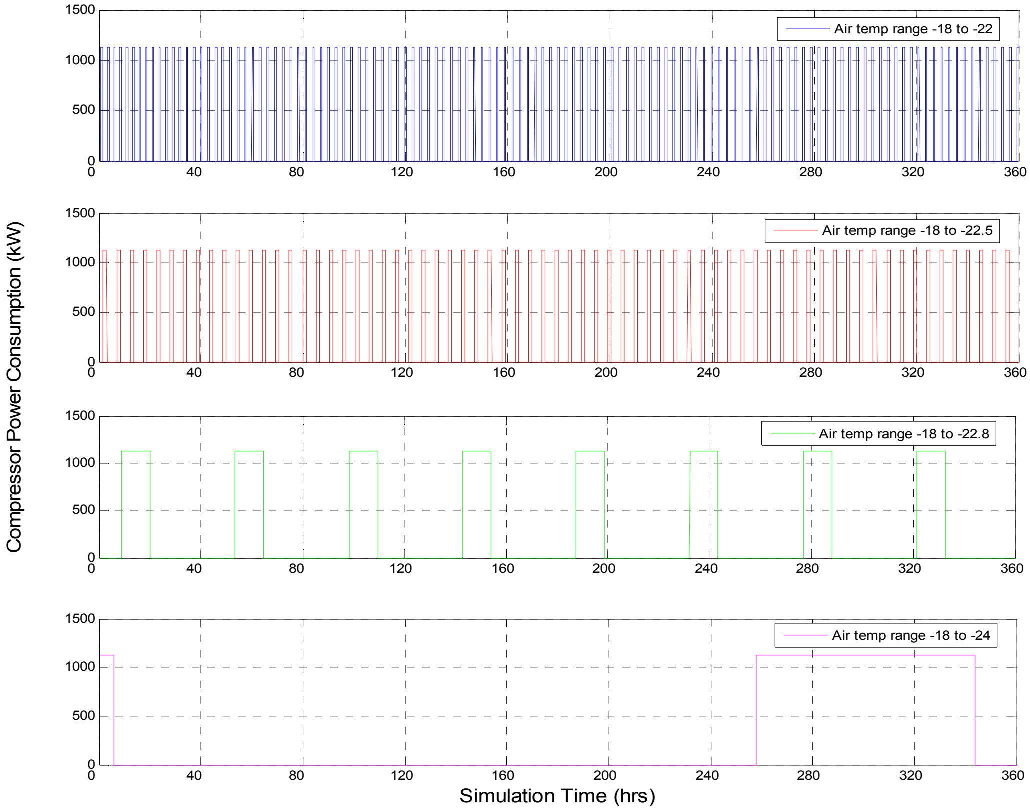

Figure 15 Comparison of simulated compressor cycling with varying air temperature limits

A closer look at the temperature profiles that are predicted by the simulations (Figure 16) reveals an explanation of what is going on. Please note the very different scales for the air and product temperatures. From the start of the simulation time (timestamp of 0 hours), it can be seen that product temperature is steadily rising as the warmer air transfers heat to the colder product. The air temperature is also steadily rising (but does not show up on the scale shown) because, despite losing heat to the product, it is gaining heat from the much warmer outside environment.

Just before the hour 2 timestamp, the air temperature reaches -18°C and the compressors switch on. The air temperature quickly drops as the heat transfer to the compressors is much higher than from the outside or the product. When it reaches the lower temperature limit (set at -22.5°C but due to the time step of the simulation, there is a slight overshoot) the compressors are switched off. Shortly after the compressors were switched on, the temperature of the air fell below that of the product and the heat transfer reversed

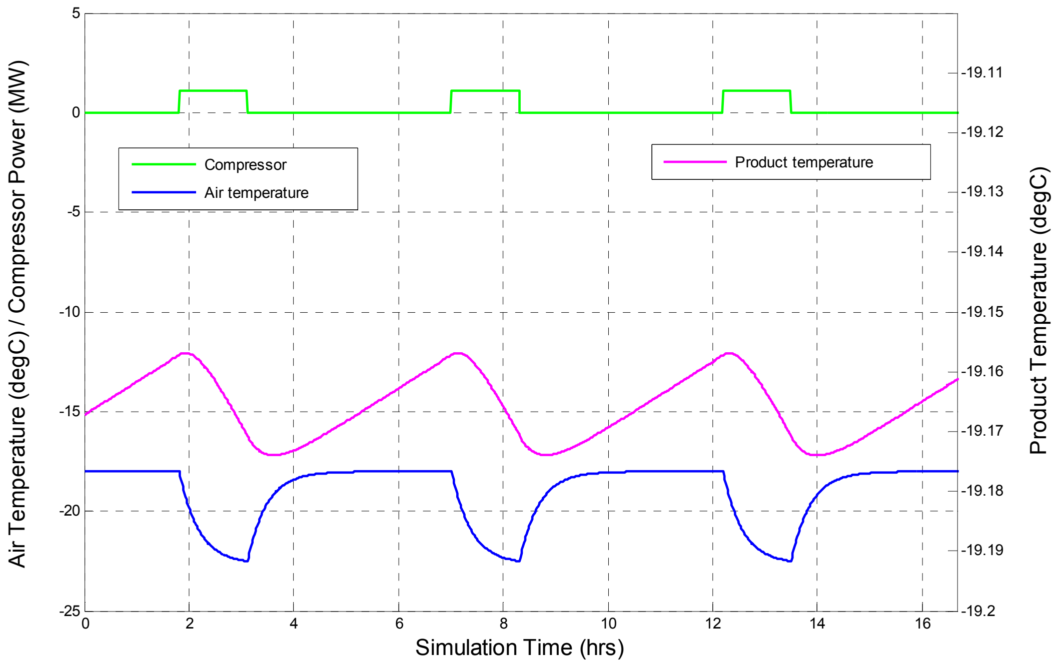

Figure 16 Profiles of temperatures and compressor cycling for air temperature limits of -18 to -22.5°C

direction (heat flowing from the product to the air) and thus the product temperature reduces. The product temperature continues to fall once the compressors are turned off again but not for long because the heat flow to the air from outside starts to increase the air temperature again. The air temperature rises again quite quickly until it reaches the same temperature as the product, at which point the rate of increase slows because the heat transfer from outside is somewhat counteracted by the heat transfer to the cooler product. The cycle then repeats itself.

Salient points arising from these observations:

- The simulations show that, as predicted, the air temperature varies quickly whilst the product temperature varies slowly. This is due to the very different heat capacities and means that, in order to act as a store of energy, the temperature of the product must be varied further than at present. The air mass stores very little energy itself.
- The compressor cycling depends heavily on the temperature range that is set for three reasons:
  a) The mass of air takes longer to cool because more heat transfer is required
  b) The cooler the air becomes the more heat transfer in from the outside (there would, in fact, come a stage at a low enough temperature at which the heat

inflow from the outside would balance the heat transfer to the compressors and the air temperature could not be lowered any further.)

c) The product average temperature lowers and thus is able to absorb more heat transfer when the compressors are off.

(In reality there is also the additional reason that the compressor efficiency drops off the colder the air temperature becomes.)

- There is an intricate interplay between the relative temperatures of the three bodies (the outside, the air, and the product) and their heat capacities (outside – infinite, the air – small, the product – large).

Observations concerning the simulation model:

- The heat transfer depends not only on the temperature difference but also on the surface area in contact between the two bodies. In this model, each cubic metre of product is assumed to have six square metres of surface area.
- The heat transfer coefficient and heat capacities are taken as constant, i.e. it is assumed that there is no temperature gradient within the bodies and that the whole of the surface area is in contact with the core temperature of the other body.

6.2 Simulations including wind power

Following on from the relatively simple simulations above, the next progression was to look at how the availability of wind power would affect the compressor cycling if there was an attempt to run the compressors when there was sufficient wind power – in effect to “store” the wind energy. The aspect that was to be observed was the change in the use of energy from the electricity supply grid and electricity delivered to the grid depending on the wind turbine capacity installed.

For these simulations, the thermostatic limits were kept the same, namely -18 to -22.5°C, which the normal controller would work to. A base case was run without any wind input and then the number of 300kW wind turbines was increased step by step to see the effect on the energy exchange with the grid. The controller (known as “the wind-noticing” controller) was able to switch on individual compressors when it considered there was sufficient wind energy to be stored. It could, likewise, switch off compressors when there was insufficient wind energy. The switch-on and switch-off limits could be set as percentages of the ratings of the compressors (i.e. this set what was considered as “sufficient” wind power) and they were also varied in a further set of simulations to see the impact this had. In the preceding simple simulations, there was only one compressor modelled. In the simulations that follow there are three compressors with the same combined power consumption as all three in the simple simulations.

6.2.1 Wind-noticing controller simulation results

A graph of the partial output of one of the simulations is shown in Figure 17. This shows examples of incidences of the compressors being switched on by the thermostatic controller overriding the wind-noticing controller when the air temperature has reached the upper limit. It also shows instances of the wind-noticing controller switching on the compressor when there was sufficient wind and switching it off when there was a lack of sufficient wind.

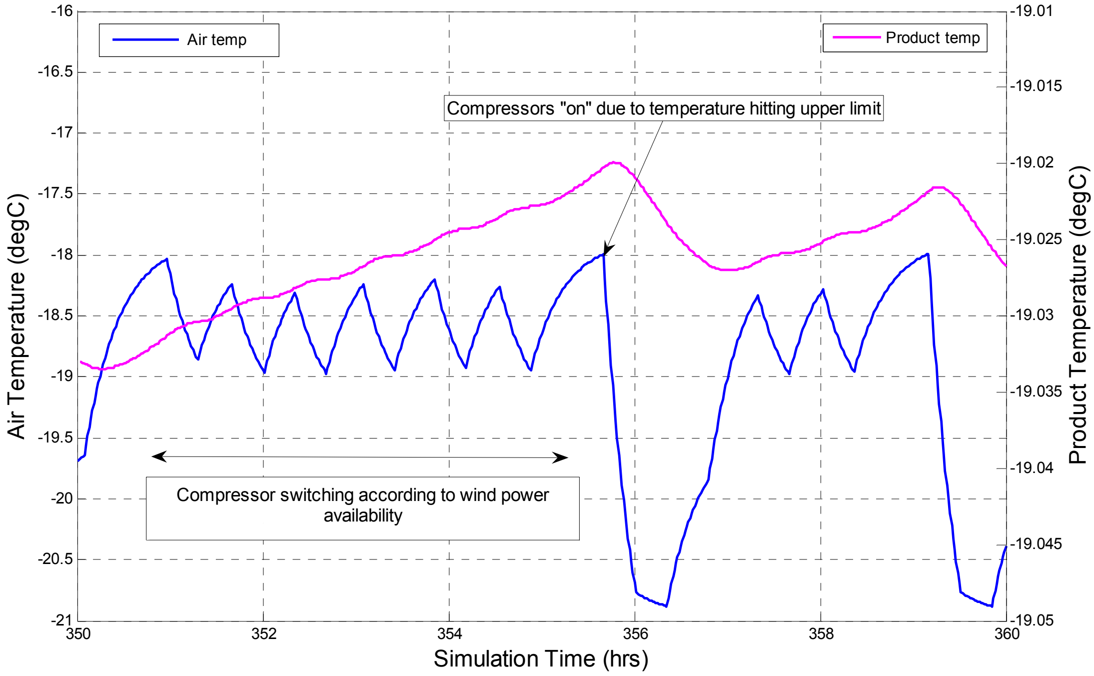

Figure 17 Temperature responses to compressor actions and controller signals

Figure 18 shows the various power flows during a selected period of one of the simulations. The periods when a compressor is off show that the wind power generated is being fed to the grid. Conversely, when a compressor is on the wind power being produced is used with the deficit being made up from the grid up to the power of the compressor.

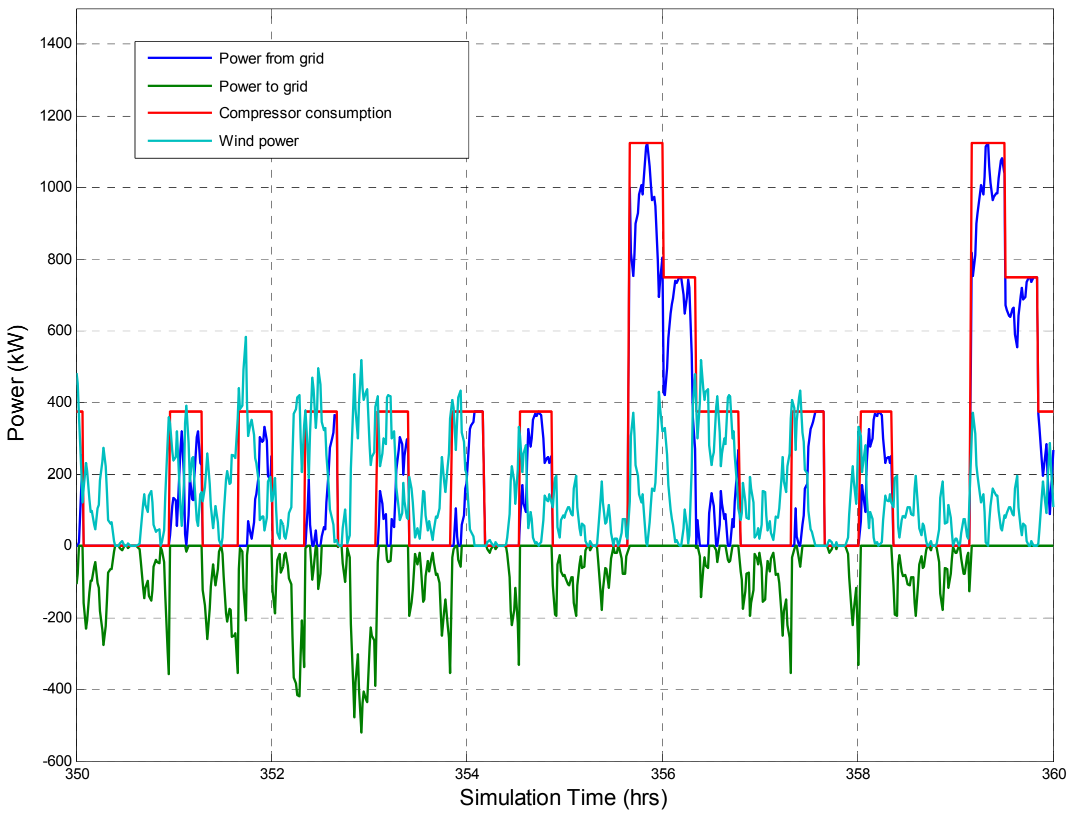

Figure 18 Power flows to/from the grid, wind power generation and compressor consumption

A summary of the results of the two sets of simulations is shown in Figure 19, which shows that the wind-noticing controller is acting as expected, that is, as more wind capacity is added more is being "stored" in the cold store and less energy is being required from the grid. A lowering of the switch-on threshold (from 80% of the rated power of one compressor to 60%) also shows that the fall in energy being taken from the grid is more rapid.

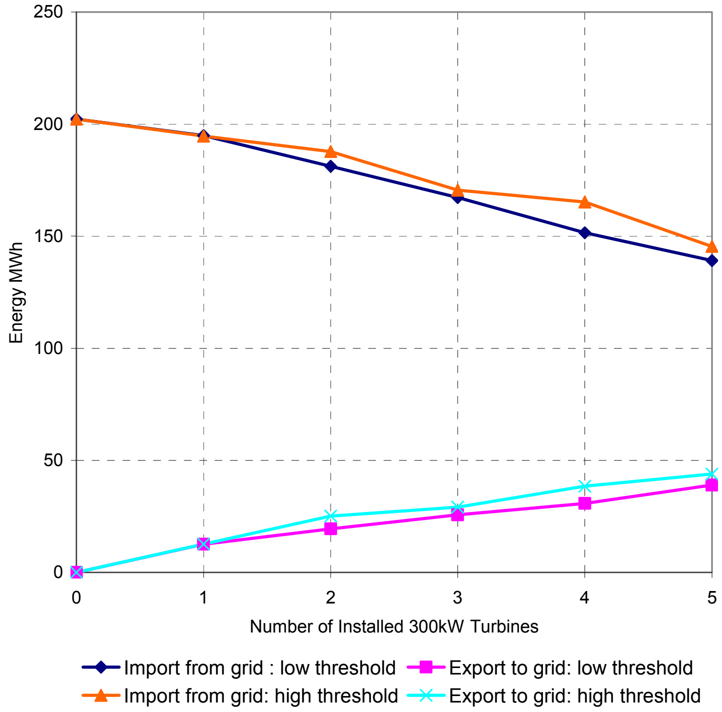

Figure 19. Impact of installed wind capacity on the energy exchange with the grid

6.3 Basic simulations with Bergen-op-Zoom model

The previous sections have shown that the cold store model and the wind input can be combined effectively. The next step was to expand the model to approximate a cold store the size of the Partner Logistics' store in Bergen-op-Zoom, Holland. Important considerations were:

- Size of cold store building and amount of product stored.
- Cooling capacity and energy consumption of the refrigeration equipment.
- Energy consumption of other equipment.
- Inclusion of the delivery of frozen product at approximately -7°C.
- Accounting for the continual removal of product at approximately -18°C.
- Heat transfer area of a pallet of product.
- Operational air temperature limits.
- Outside (ambient) temperature data.

A very important part of this work was the collection of actual operational data by Progmatic, an industrial control company based in Steenbergen, Holland. This data (both temperature and power consumption) was used to assess the characteristics of the cold store and to provide a certain degree of verification of the model's performance.

When the appropriate values (see Appendix A for a table of values used in the simulation model) and considerations as highlighted above were included in the model, a simulation was run for a year using temperature data from the Dutch Meteorological Service (KNMI). The temperatures for the ambient air, the cold store air and the product as simulated by the model are given in Figure 20.

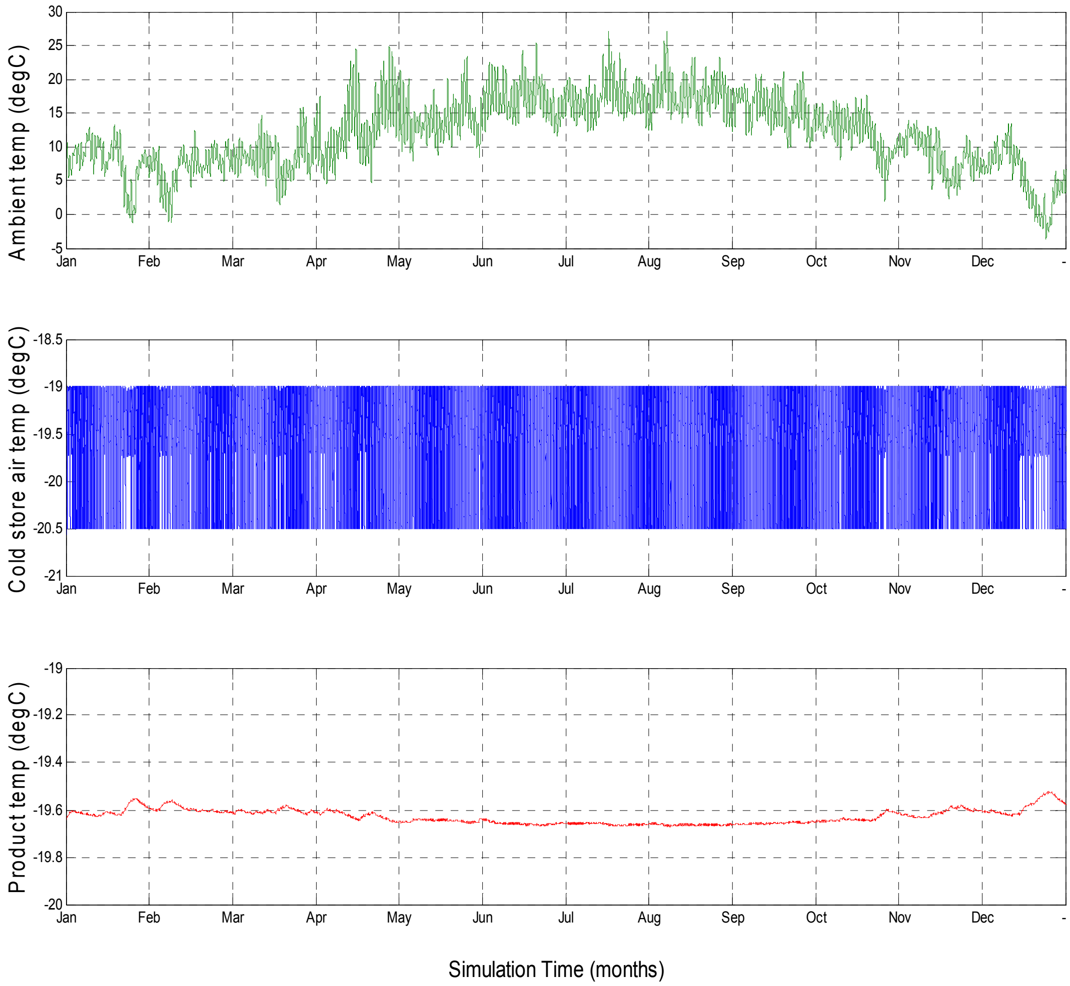

Figure 20 Simulation using model of Bergen-op-Zoom cold store for the whole of 2007

Using the data measured by Progmatic, the energy consumption of the various equipment in the cold store could be identified and thus the total electricity consumption could be split according to the type of equipment:

- Compressors.
- Other refrigeration equipment associated with refrigeration that varies with the compressor use.
- Equipment not used directly for refrigeration (cranes, oxygen reduction equipment, etc.) and considered as an average (constant) consumption.

This allows the simulation results (which only give the consumption of the compressors) to be adjusted to give an indication of the total consumption. The following are, therefore, comparable figures for the consumption of all the equipment types listed above.

Measured consumption for November 2007: 823 000 kWh

Simulated consumption for November 2007: 734 000 kWh

This shows that the model gives a reasonable approximation of the energy consumption, estimating approximately 90% of the measured consumption.

For 2007 as a whole, the simulation gives a total consumption of 9.3 M kWh, which again, compares quite favourably with PAL's estimate of around 12 M kWh total energy use in a year.

6.4 Discussions, recommendations and conclusions

The cold store model within IPSYS has been demonstrated to give reliable and representative results for a number of different sizes of facility and, whilst there are a number of further refinements that could be included, it is felt that the results so far show an appropriate level of accuracy.

The handling of increasing wind energy in the simulation model has been demonstrated to be satisfactory.

7 Final WP3 discussions and conclusions

The necessary aspects have been prepared to enable the simulation of cold stores within an energy system with a high penetration of wind power. A number of set-ups have been simulated within the IPSYS simulation platform and shown to give sufficiently accurate results.

Simulations have been carried out with a single cold store and an increasing amount of wind power in the system. A simple control strategy has shown that it is indeed possible to "store" the wind energy even without any forecasting.

The NWCS from Work Package 5 has been translated into C++ and developed so that it can now function within a system that requires real-time decisions.

The simulation of cold stores to assess how the Night Wind concept can best assist the integration of wind power at the European level have not be carried out but would have been the major result from the additional time requested at the project meeting in March 2008. This extension of time was not granted and so only some of the expected results have been obtained. Nevertheless, the work possible is considered significantly complete, although it is acknowledged that there has been a delay in the presentation of this report. It should be noted that it was not possible to address the new aspects of Task 3.7 "Verification of simulation results" as there was no implementation of the night wind concept at the demonstration site (Task 7).

References

[1] Bindner, H. et al., IPSYS – “A Simulation Tool for Performance Assessment and Controller Development of Integrated Power System Distributed Renewable Energy Generated and Storage”, WREC VIII, Denver, Colorado.

[2] Team CoolPack, Department of Energy Engineering, Technical University of Denmark “CoolPack – Simulation tools for refrigeration systems”, paper presented at the 1999 Scandinavian Simulation Society Conference (Sims99).

[3] Matlab, The MathWorks, Inc. Version 7.0.1.24704 (R14).

[4] D. E. Goldberg, Genetic Algorithm in Search, Optimization and Machine Learning. Reading, MA: Addison-Wesley, 1989, pp. 1–15

[5] Matthew Wall. (1996, August). GAlib: A C++ Library of Genetic Algorithm Components. Version 2.4.

Appendix A: Cold store model data

Modelling data used for representing the Bergen-op-Zoom cold store facility. Table is a development of that in deliverable D.3.1 “Scenarios and Input Needs”.

Modelling input information

Item	Value(s)	Unit	Source*
Cold store volume (Phase I and II)	577500	m^3	1
Cold store surface area (Phase I and II)	38620	m^2	1
Volume of a pallet of products	3.16	m^3	1
Surface area of a pallet of products	13.56	m^2	1
Product volume at 100% capacity	320855	m^3	1
Product volume at 80% capacity (allows room for incoming product)	251583	m^3	calculation
Product volume at 70% capacity (allowance for heat capacity ‘loss’ of products being removed at -18°C)	219523	m^3	calculation
Product surface area at 70% capacity	942002	m^2	calculation
Cold store heat transfer coefficient	0,4	W/ m^2K	2
Product heat transfer coefficient	1,5	W/ m^2K	2
Density of product	1100	kg/ m^3	2
Density of air	1,4	kg/ m^3	2
Relative humidity air	90	%	2
Ambient pressure air	101325	Pa	standard
Product heat capacity	4,4	kJ/kgK	2
Air heat capacity	1,007	kJ/kgK	2
Product initial temperature (i.e. start of simulation run)	-18,5 to -19.8	°C	derived from 3
External temperature time series	~-5 to 33	°C	4
Compressor power consumption ratings 1) CO_2 2) R410A	 125 250	 kW kW	 2, 3 & 5 2, 3 & 5
Number of compressors 1) CO_2 2) R410A	 3 3	 - -	 2 2
Compressor efficiency (System COP) (dependent on external temperature)	1,6 to 2,15	-	2 & 6
Incidental heat sources in cold store	-	W	

Mass of product inflow/outflow	~ 0 to 9000	kg/hr	
Pallet delivery at -7°C	1500	pallets/day	7
Cooling load of incoming products	800	kW	calculation
Cold store controller logic – one compressor set is ‘on’ all the time and on average there are 1.7 – 2 compressor sets working.	-	-	3
Upper air temperature (on average)	-19	°C	3
Lower air temperature (on average)	-20.5	°C	3
Upper air temperature (allowed in model)	-18	°C	-
Lower air temperature (allowed in model)	-24	°C	-
Upper product temperature	-18	°C	8
Lower product temperature	-24	°C	8
Wind turbine rated output	~300 - 850	kW	9
Wind turbine active power curve	-	kW vs. m/s	9
Wind turbine active/reactive power curve	-	kW vs kVAr	9
Number of wind turbines	0 to 8	-	9
Number of cold stores	1	-	-
Other consumer load time series	-	kW	-
Wind power time series	-	m/s	9
Electricity price time series	-	€/kWh	9

*Sources:
1 Specification file (Deliverable 2.1)
2 Project report “Simulating dynamic behaviour of refrigeration plants with “Coolpack” software”.
3 Measure data from Progmatic
4 Dutch Meteorological Service (KNMI station at Vlissingen)
5 Data sheets for compressors
6 Calculation sheet “Refrigeration plant PAL I&II.xls”
7 Project technical meeting at Progamtic, October 2007
8 Values assumed as information regarding allowable temperature variation of product has not been forthcoming from WP 4.
9 Information from ESSENT: email Rene Reindeers to Tom Cronin 20-03-2007 & data sheets “Halsteren production.xls” and “sourcing and sales nightwind 2006.xls”. Some information also derived from wind turbine type (Vestas V52).